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Liquid Hydrogen Mass Flow Through a Multiple Orifice Joule-Thomson Device

S. Stephen Papell
Analex Corporation
Brook Park, Ohio

and

Ted W. Nyland and Naseem H. Saiyed
Lewis Research Center
Cleveland, Ohio

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LIQUID HYDROGEN MASS FLOW THROUGH A MULTIPLE ORIFICE

JOULE-THOMSON DEVICE

S. Stephen Papell
Analex Corporation
3001 Aerospace Parkway
Brook Park, Ohio 44142

and

Ted W. Nyland and Naseem H. Saiyed
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

Liquid hydrogen mass flow rate, pressure drop, and temperature drop data were obtained for a number of multiple orifice Joule-Thomson devices known as Visco Jets. The present investigation continues a study to develop an equation for predicting two phase flow of cryogenics through these devices. Liquid nitrogen flow data, single (liquid) and two phase, and a data correlating equation that predicted it, was developed and presented in an earlier report. The correlation was a modified version of a flow prediction equation from the Visco Jet manufacturer. Current effort extends this equation by testing it with liquid hydrogen.

The test apparatus design allowed isenthalpic expansion of the cryogen through the Visco Jets. The data covered a range of inlet and outlet operating conditions. The inlet pressure and temperature range was 27 to 65 psi and 34 to 46 R, respectively. The outlet pressure and temperature range was 2.5 to 60 psia and 26 to 46 R, respectively. The mass flow rate data range—single phase or two phase—was 0.015 to 0.98 lbm/hr.

The manufacturer's equation was found to overpredict the single phase hydrogen data by 10 percent and the two phase data by as much as 27 percent. Two modifications to the equation resulted in a data correlation that predicts both the single and two phase flow across the Visco Jets. The first modification was of a theoretical nature, and the second strictly empirical. The former reduced the spread in the two phase data.

It was a multiplication factor of $1-X$ applied to the manufacturer's equation. The parameter X is the flow quality downstream of the Visco Jet based on isenthalpic expansion across the device. The latter modification was a 10 percent correction term that correlated 90 percent of the single and two phase data to within a ± 10 percent scatter band.

Nomenclature

| | |
|------------|---|
| C_v | equivalent flow coefficient, 1 C_v = 1 gpm H_2O per 1 psid at 60 °F |
| h_g | saturated vapor enthalpy at Visco Jet outlet pressure, Btu/lbm |
| h_l | saturated liquid enthalpy at Visco Jet outlet pressure, Btu/lbm |
| h_t | enthalpy at Visco Jet inlet pressure and temperature, Btu/lbm |
| $Lohm$ | Lohm rating (flow resistance), 1 $Lohm$ = 100 gpm H_2O per 25 psid at 80 °F |
| M | flow rate, lbm/hr |
| S | specific gravity, density at Visco Jet inlet pressure and temperature (lbm/ft ³)/62.4 |
| X | Visco Jet exit quality |
| ΔP | pressure drop across the Visco Jet, psid |

Introduction

Any mission requiring long duration with humans uses cryogenics as propellants and as life supporting fluids. An endeavor of Mars Mission magnitude increases the quantity and the storage life of the cryogen to levels much greater than any previous missions. This places unique technology requirements for managing large quantities of cryogenics for long durations. One such technology addressed in this report is tank pressure control.

The space-based cryogenics are stored at or near their saturation points. The heat leaks, however small, cause the cryogen to evaporate and raise the tank pressure. Unless controlled, the pressure will increase beyond the tank's maximum operating pressure. A technique that solves such a scenario uses a Thermodynamic Vent System.¹ A Joule-Thomson (JT) device is used to cool a small quantity of bulk cryogen. This cooler quantity serves as the colder fluid in a heat exchanger placed within the bulk cryogen. The heat exchanger transfers the bulk cryogen heat to the colder fluid which is then expelled overboard. Ideally, the heat input to the bulk cryogen is equal to the energy expelled overboard. In a steady-state operation the tank pressure remains constant.

Any expansion device such as an orifice, a regulator, or a needle valve cools the fluid as long as the JT coefficient for the process remains positive. A Visco Jet^{*} is one such device. It is proposed for aerospace systems because of its simplicity.¹ Its primary advantage over a valve is the absence of moving parts and the relatively high flow rates obtained with large orifice openings. Visco Jets were designed as miniature hydraulic flow control components using a "multiple orifice" concept to induce a pressure drop in the line. The flow path includes many orifices in series containing spin chambers to enhance the pressure drop. This design increases the orifice size to five times that of a single orifice for the same pressure drop. The larger orifice also reduces the possibility of clogging due to solid contaminants in the line.

^{*} Lee Corporation, Westbrook, CT.

Since the Visco Jet is a multiple orifice device the standard orifice flow equations cannot predict the flow rate. Therefore, the manufacturer has created term, liquid ohms (*Lohm*), to measure the flow resistance. This term is included in an equation² (defined herein as the Lee Equation) to predict single phase (liquid) flow rates:

$$M = (10\,000/Lohm)(\Delta P S)^{1/2} \quad (1)$$

When corrected for specific gravity (*S*) this equation is valid for any fluid listed in Ref. 2. The cryogenics are not mentioned in this list. The multiple orifice design reduces the onset of cavitation with hydraulic fluids. However, cavitation is inevitable with cryogenics because they are stored at or near their saturation conditions. An isenthalpic expansion through a JT device for these fluids leads to an end state in the two phase region. This reduces the flow rate predicted by the Lee Equation. An equation to predict single and two phase rates was not developed until the initiation of this test program.

This report continues the study to obtain liquid nitrogen and liquid hydrogen flow rate and pressure drop data through Visco Jets with different *Lohm* ratings. The liquid nitrogen data were correlated and reported in Ref. 3. It was shown that the Lee Equation effectively predicted the single phase nitrogen flow but overpredicted the two phase flow. A modified version of the Lee Equation:

$$M = (10\,000/Lohm)(\Delta P S)^{1/2}(1 - X) \quad (2)$$

greatly improved the correlating results. The parameter *X* is the flow quality downstream of the Visco Jet. It is based on isenthalpic expansion across the device:

$$h_t = X h_g + (1 - X)h_l$$

or

$$X = (h_t - h_l)/(h_g - h_l) \quad (3)$$

The flow becomes two phase if the enthalpy prior to expansion (h_t) is greater than the saturated liquid enthalpy (h_f) after expansion.

The liquid nitrogen data³ covered a range of operating conditions. The inlet pressure and temperature range was 30 to 60 psia and 118 to 164 R, respectively. The outlet pressure ranged from 2.8 to 55.8 psia and the flow rate from 0.04 to 4.0 lbm/hr. The Visco Jet *Lohm* ratings were between 17 000 and 243 000 (equivalent C_v values of 1×10^{-3} to 8×10^{-5}). All the single phase data and 85 percent of the two phase data fell within ± 10 percent of that predicted by Eq. (2).

In this study, liquid hydrogen single and two phase flow data were obtained with the same test apparatus. This report presents the results of applying this data to the Lee Equation.

Experimental Equipment

The Joule-Thomson device test apparatus was designed as a teststand mounted on a wheeled cart to enable a high degree of flexibility within the test program. Both liquid hydrogen or liquid nitrogen could be run as the test fluid without system modification. For the liquid nitrogen study³ the cart was located within a test cell but for the present liquid hydrogen study the cart was wheeled outdoors and placed on a cement pad located about 40 ft from the cell door. In this position the test apparatus and supply dewar were shielded by dirt mounds to satisfy safety requirements. A design goal for the test apparatus was to minimize the heat leak into the test article to maintain the flow process as close to isenthalpic as possible.

Flow System

A system schematic of the apparatus is shown on Fig. 1. Liquid hydrogen flows from a 150 gal supply dewar through a vacuum jacketed line connected to the base flange of the test chamber. The cylindrical vacuum chamber which houses the Visco Jet as part of the flow system is 10 in. in diameter with a height of 19 in. The entire apparatus, including the test chamber and flow system piping, is stainless steel. The liquid flow control valve between the supply dewar and the test

chamber is vacuum jacketed and pneumatically actuated. Pressure regulating valves downstream of the flow system piping are also pneumatically actuated but not vacuum jacketed. Vapor vent on/off valves for routing the flow through a bank of flowmeters are controlled by solenoid valves that are housed within a nitrogen purged box for safety requirements.

The flow system has one primary and one secondary Visco Jet. The primary jet is the test article and the secondary jet is part of a heat exchanger system. Liquid hydrogen from the supply dewar enters the test chamber flow system, via a flange feed through port, and flows upward where it is divided into three parts by a cross in the line. The test fluid turns downward and flows through a double tube type heat exchanger, an electrically heated coil, the primary Visco Jet, the air heat exchanger, and a bank of flowmeters before discharging through an air ejector to the atmospheric vent. The test fluid is cooled in the heat exchanger and heated by the heater coil. By selectively using the heat exchanger and the heater coil a wide range of inlet temperatures, from significant subcooling to near saturation, are achieved. The test fluid, after expansion, is completely vaporized in an air heat exchanger prior to entering the bank of gas flowmeters. The primary ejector pump, between the flowmeters and the vent, is operated to simulate discharging to space conditions.

The aforementioned cross in the line diverts some of the flow through the secondary Visco Jet. This is the outer flow of the heat exchanger and is discharged through the secondary air ejector to the vent system. The balance of the flow, labeled bypass flow in Fig. 1, enters the cold wall coils and discharges to the atmosphere.

Photographs of the flow system and components within the vacuum chamber are shown in Figs. 2 and 3. In Fig. 2, the vacuum tank cover is removed showing the exterior view of the cold wall and the coolant flow coils brazed to the wall itself. The cold wall is a thin stainless steel shell. It is surrounded by an aluminized mylar thermal shield (not shown) to reduce radiation from the test chamber wall to the cold wall. Since most of the

fluid entering the flow system was bypassed, a nominal flow rate was determined during initial operations to maintain the cold wall at near constant temperature. In Fig. 3, the cold wall is removed to reveal the flow system plumbing that includes the primary and the secondary Visco Jets. The lines, 1/4-in. seamless tubing with a 0.028-in. wall thickness, are shaped to fit into the cold wall confined area and to relieve stress during thermal cycling.

Test Article

The Joule-Thomson device (Visco Jet) used in this study is essentially a group of orifices in series contained in a fitting for installation within a flow system. Figure 4, taken from Ref. 2, is a schematic of the orifice arrangement within one of several disks. The resistance to flow is generated by a set of complex flow passages within the disk. A set of these disks, arranged in series, are mounted in the fitting perpendicular to the flow. The flows direction of rotation changes many times within the device. This results in a pressure drop much greater than would be obtained with normal metering orifices of the same diameter.

Four sets of Visco Jets, with different *Lohm* ratings, were purchased from the manufacturer. Each set consisted of six individual units of similar *Lohm* rating. Each Visco Jet was calibrated by the NASA Lewis Research Center Flow Lab with water and the results checked against the nominal *Lohm* ratings supplied by the manufacturer. Table 1 lists the manufacturer's specified *Lohm* ratings and the calculated *Lohm* ratings. The difference between the specified and calculated ratings varied as much as 8.7 percent. Therefore, only the calibrated values were used in calculations. The specific Visco Jets used for this study are noted in Table 1.

Instrumentation

Figure 1 displays the instruments used in this study. The pressure measurements were made with strain gage type transducers, and the temperature measurements with silicon diode sensors. The fluid pressure and temperature data were obtained upstream and downstream of the primary

Visco Jet. The temperature of the bypass flow was measured upstream of the bank of flowmeters. Instruments were calibrated prior to the initial data runs and after testing was completed. During the testing, continuous checks were made by comparing the output of instruments that were under identical test conditions.

Mass flow rates through the primary Visco Jets, after warming to ambient conditions, were measured by a bank of flowmeters. Four thermal conductivity type mass flowmeters were used to cover the 100 to 1 mass flow rate range.

Data Acquisition System

Pressure and temperature measurements as voltage signals from the various sensors were multiplexed, digitized, and recorded on a dedicated desk top computer. The computer converted the voltage measurements to engineering units. Test conditions were displayed, on line, in engineering units on the computer monitor and the data stored on the computer's hard disk. The data were then transferred to a floppy disk for further processing.

Experimental Procedure

Prior to testing, the Visco Jet chamber housing was evacuated to about 35 μm of mercury at which time the vacuum pump was isolated from the apparatus and shut off. The vacuum system integrity was established by noting an insignificant pressure gain over a 24 hr time interval. During testing, the vacuum was monitored with a video camera focused on a vacuum gage that was mounted on the outer wall of the test chamber.

A test run was initiated by purging the system piping with gaseous helium to eliminate water vapor and air. The liquid hydrogen supply dewar was pressurized with helium gas to a desired operating pressure. The outlet flow valve on the supply dewar was then remotely opened to chill down the entire test apparatus by flowing liquid hydrogen through the system piping and discharging to an atmospheric vent.

The controlled parameters for setting up the test conditions were inlet and exit Visco Jet

pressures, inlet Visco Jet temperature, and bypass flow rate. A typical data run consisted of establishing a fixed pressure and temperature upstream of the Visco Jet and then setting the downstream pressure over a range of pressure settings. In each run, the data was recorded for 20 readings at 5 sec interval and then averaged for computational purposes. Data presented here are the averaged values.

Liquid hydrogen data covered a range of inlet and outlet operating conditions. Inlet pressure and temperature range was 27 to 65 psia and 34 to 46 R, respectively. Outlet pressure and temperature range was 2.5 to 60.7 psia and 28 to 46 R, respectively. The mass flow rates varied from 0.015 to 0.98 lbm/hr. The basic data, quality, measured flow rates, and predicted flow rates are listed in tables 2(a) to (d) for Visco Jets with *Lohm* ratings of 17 180, 43 070, 86 960, and 252 300, respectively. The column headings are listed at the end of the table.

Data Presentation and Correlation

The main contribution of the initial liquid nitrogen study³ was an equation that predicted two phase mass flow rates through multiple orifice Joule-Thomson devices known as Visco Jets. The Lee Equation predicted single phase flow rates but overpredicted the two phase flows. The two phase data were correlated with a modification to the Lee Equation. The modification was a multiplying factor of $1-X$. The parameter X represented the quality based on isenthalpic expansion across the Visco Jet. It was anticipated, since the modification was of a theoretical nature, that the modified Lee Equation could predict the liquid hydrogen data presented in table 2 of this report.

The single phase ($X = 0$) hydrogen data for the 17 180 *Lohm* Visco Jet are plotted in Fig. 5 as measured flow versus that predicted by the Lee Equation. The solid line on the plot represents perfect agreement between the measured and predicted data. Figure 5 shows that the Lee Equation overpredicts the measured flow rate data by about 10 percent with some data scatter. The overprediction differs from the previously men-

tioned nitrogen single phase data which correlated well with the Lee Equation.

The two phase ($X > 0$) hydrogen data for the same Visco Jet are plotted in Fig. 6 as measured flow versus that predicted by the Lee Equation. Correlation of this data with the Lee Equation was not anticipated since the Lee Equation was developed to predict only single phase flow. Figure 6 shows an overprediction of as much as 27 percent. Figure 7 shows the results of $(1-X)$ multiplying factor to the Lee Equation. A marked reduction in the data scatter is noted. But, the correction still overpredicts the measured data by about 10 percent. A correlation of both the single and two phase data is achieved with a correction coefficient of 0.90:

$$M = 0.90(10\ 000/Lohm)(\Delta P\ S)^{1/2}(1 - X) \quad (4)$$

The single and two phase data for the 17 180 *Lohm* rating Visco Jet were then applied to Eq. (4) and the results plotted in Fig. 8. This figure shows that 90 percent of the data falls within a ± 5 percent scatter band. This gives greater confidence in the applicability of the correlation.

The liquid hydrogen data from all Visco Jets tested are shown in Fig. 9 with predicted flow rates determined by Eq. (4). This figure shows that 90 percent of the data falls within a ± 10 percent scatter band. This band is greater than that shown in Fig. 8. This is attributed to the greater flow instabilities at the lower flow rates.

Summary of Results

A test apparatus, capable of flowing either liquid nitrogen or liquid hydrogen, was constructed to gather data for single and two phase flow across Joule-Thomson devices known as Visco Jets. Liquid nitrogen flow data and a correlation that predicted it was developed and presented in an earlier report. In that study the manufacturer's flow prediction equation, for noncryogenic fluids, was modified by an $1-X$ multiplying factor. The parameter X was the quality downstream of the

Visco Jet and was based on isenthalpic expansion across it. The modified version predicted the nitrogen single and two phase flow data very well.

In the current effort liquid hydrogen was tested with Visco Jets of similar *Lohm* rating. These devices had flow resistance (*Lohm* rating) of 17 180, 43 070, 86 969, and 252 300. The data covered a range of inlet and outlet operating conditions. The inlet pressure and temperature range was 27 to 65 psia and 34 to 46 R, respectively. The outlet pressure and temperature range was 2.5 to 60 psia and 26 to 46 R, respectively. The mass flow rate data range—single phase or two phase—was 0.015 to 0.98 lbm/hr.

The manufacturer's flow prediction equation, for noncryogenic fluids, overpredicted the single phase (liquid) hydrogen data by 10 percent and the two phase data by as much as 27 percent. The multiplying factor of 1-X considerably reduced the data scatter. However, a correction factor of

10 percent was still needed. The modified and corrected version of the manufacturer's flow prediction equation predicts 90 percent of the hydrogen single and two phase data to within a ± 10 percent scatter band.

References

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2. Lee Company Technical Hydraulic Handbook, Westbrook, CT, 1984.
3. Papell, S.S., Saiyed, N.H., and Nyland, T.W., "Acquisition and Correlation of Cryogenic Nitrogen Mass Flow Data Through a Multiple Orifice Joule-Thomson Device." NASA TM-103121, 1990.

TABLE 1.—VISCO JET WATER CALIBRATION

| TEST RESULTS | | | | |
|-----------------------|----------------|-------------------------|---------------------------|------------------|
| <i>Lohm</i> rating | Unit | Flow rate, lbm/hr | Calculated <i>Lohm</i> | Percent error |
| 17 600 | 1 | 2.948 | 16 950 | -3.70 |
| | 2 | 2.672 | 18 700 | 6.24 |
| | 3 | 2.864 | 17 440 | -.88 |
| | 4 | 2.896 | 17 250 | -1.98 |
| | ^a 5 | 2.908 | 17 180 | -2.38 |
| | 6 | 2.938 | 17 000 | -3.38 |
| 41 000 | 1 | 1.174 | 42 560 | 3.80 |
| | ^a 2 | 1.160 | 43 070 | 5.05 |
| | 3 | 1.218 | 41 020 | .05 |
| | 4 | 1.216 | 41 090 | .21 |
| | 5 | 1.176 | 42 480 | 3.60 |
| | 6 | 1.182 | 42 270 | 3.10 |
| 80 000 | 1 | .604 | 82 640 | 3.30 |
| | ^a 2 | .574 | 86 960 | 8.70 |
| | 3 | .610 | 81 830 | 2.28 |
| | 4 | .582 | 85 760 | 7.21 |
| | 5 | .604 | 82 640 | 3.30 |
| | 6 | .562 | 88 820 | 11.00 |
| 243 000 | 1 | .194 | 257 500 | 5.98 |
| | ^a 2 | .198 | 252 300 | 3.84 |
| | 3 | .198 | 252 300 | 3.84 |
| | 4 | .198 | 252 300 | 3.84 |
| | 5 | .196 | 254 900 | 4.90 |
| | 6 | .200 | 249 800 | 2.80 |

^aData obtained with these Visco Jets.

TABLE 2.—VISCO JET DATA AND CALCULATED RESULTS

(a) Visco Jet 17 180 Lohm

| Pressure drop across visco jet, psia | Flow rate, lbm/hr | | | | Visco jet inlet | | Visco jet outlet | | Quality |
|--------------------------------------|-------------------|--------------|-----------------------|----------------------------|-----------------|-----------------|------------------|-----------------|---------|
| | Measured | Lee equation | Modified Lee equation | 0.9x modified Lee equation | Pressure, psia | Temperature, °R | Pressure, psia | Temperature, °R | |
| 59.99 | 0.98 | 1.18 | 1.04 | 0.93 | 65.00 | 40.48 | 5.01 | 32.47 | 0.12 |
| 52.12 | .96 | 1.10 | 1.03 | .93 | 64.21 | 39.90 | 12.09 | 36.50 | .06 |
| 39.65 | .83 | .96 | .94 | .85 | 64.17 | 40.55 | 24.52 | 40.50 | .02 |
| 29.59 | .72 | .83 | .83 | .75 | 64.79 | 40.66 | 35.19 | 40.49 | .00 |
| 16.01 | .53 | .61 | .61 | .55 | 65.07 | 40.66 | 49.06 | 40.24 | .00 |
| 4.88 | .29 | .34 | .34 | .30 | 65.68 | 40.66 | 60.80 | 40.20 | .00 |
| 5.02 | .29 | .33 | .33 | .30 | 66.18 | 44.11 | 61.15 | 43.86 | .00 |
| 18.32 | .56 | .64 | .64 | .57 | 66.25 | 44.28 | 47.93 | 44.02 | .00 |
| 30.38 | .72 | .82 | .80 | .72 | 64.80 | 44.04 | 34.42 | 43.57 | .03 |
| 39.25 | .77 | .93 | .87 | .78 | 63.88 | 44.10 | 24.64 | 41.03 | .07 |
| 47.79 | .87 | 1.06 | .94 | .85 | 52.38 | 39.30 | 4.60 | 32.17 | .11 |
| 40.32 | .84 | .97 | .92 | .83 | 52.66 | 39.21 | 12.34 | 36.52 | .05 |
| 27.43 | .66 | .80 | .80 | .72 | 51.86 | 39.47 | 24.43 | 39.20 | .00 |
| 15.89 | .50 | .61 | .61 | .55 | 51.22 | 39.53 | 35.32 | 39.07 | .00 |
| 4.63 | .27 | .33 | .33 | .30 | 50.81 | 39.68 | 46.17 | 39.22 | .00 |
| 55.77 | .95 | 1.13 | .97 | .87 | 60.78 | 42.00 | 5.01 | 32.60 | .14 |
| 47.05 | .87 | 1.04 | .94 | .85 | 59.27 | 42.02 | 12.22 | 36.50 | .09 |
| 33.07 | .77 | .87 | .84 | .76 | 57.44 | 41.90 | 24.37 | 40.80 | .03 |
| 22.28 | .62 | .71 | .71 | .64 | 57.48 | 41.71 | 35.20 | 41.43 | .00 |
| 9.78 | .41 | .47 | .47 | .42 | 57.92 | 42.24 | 48.13 | 41.69 | .00 |
| 3.74 | .27 | .29 | .29 | .26 | 57.99 | 41.87 | 54.24 | 41.36 | .00 |
| 31.84 | .72 | .86 | .77 | .69 | 35.80 | 39.36 | 3.96 | 32.08 | .11 |
| 24.57 | .63 | .76 | .71 | .64 | 35.62 | 39.45 | 11.05 | 36.35 | .06 |
| 16.74 | .56 | .63 | .61 | .55 | 35.63 | 39.46 | 18.89 | 39.00 | .02 |
| 11.62 | .47 | .52 | .52 | .47 | 35.93 | 39.45 | 24.32 | 38.99 | .00 |
| 3.80 | .28 | .30 | .30 | .27 | 36.08 | 39.26 | 32.27 | 38.84 | .00 |
| 3.50 | .26 | .28 | .28 | .25 | 36.17 | 41.52 | 32.67 | 41.01 | .00 |
| 11.48 | .47 | .51 | .50 | .45 | 36.29 | 41.62 | 24.80 | 41.06 | .03 |
| 18.50 | .57 | .65 | .62 | .56 | 36.62 | 41.25 | 18.12 | 38.96 | .05 |
| 26.33 | .63 | .77 | .70 | .63 | 36.74 | 41.58 | 10.41 | 35.98 | .09 |
| 33.01 | .67 | .87 | .74 | .67 | 36.84 | 41.61 | 3.83 | 31.57 | .14 |
| 32.19 | .73 | .88 | .81 | .73 | 36.12 | 36.51 | 3.94 | 31.64 | .08 |
| 24.53 | .68 | .77 | .75 | .68 | 35.37 | 36.10 | 10.84 | 35.31 | .02 |
| 16.24 | .50 | .63 | .63 | .56 | 34.33 | 35.63 | 18.09 | 34.92 | .00 |
| 9.17 | .37 | .47 | .47 | .42 | 33.91 | 35.89 | 24.75 | 35.20 | .00 |
| 3.14 | .22 | .28 | .28 | .25 | 33.65 | 35.52 | 30.51 | 35.02 | .00 |
| 43.27 | .79 | 1.01 | .92 | .83 | 47.42 | 37.80 | 4.15 | 31.92 | .09 |
| 35.54 | .69 | .92 | .89 | .81 | 48.44 | 37.64 | 12.91 | 36.90 | .03 |
| 24.77 | .57 | .75 | .65 | .59 | 28.82 | 40.95 | 4.05 | 32.29 | .13 |
| 17.94 | .52 | .64 | .59 | .53 | 27.82 | 40.75 | 9.89 | 36.00 | .08 |
| 8.48 | .39 | .44 | .42 | .38 | 27.05 | 41.31 | 18.50 | 39.20 | .05 |
| 33.87 | .71 | .89 | .79 | .71 | 38.84 | 40.10 | 4.97 | 32.75 | .11 |
| 26.34 | .66 | .78 | .73 | .66 | 38.16 | 40.30 | 11.82 | 36.70 | .07 |
| 14.15 | .50 | .57 | .57 | .51 | 39.26 | 40.10 | 25.10 | 38.76 | .00 |
| 3.76 | .28 | .30 | .30 | .27 | 37.66 | 39.89 | 33.90 | 38.69 | .00 |
| 44.44 | .73 | 1.00 | .83 | .74 | 48.83 | 43.62 | 4.39 | 32.40 | .17 |
| 33.73 | .67 | .87 | .78 | .70 | 48.08 | 43.73 | 14.36 | 37.80 | .10 |
| 11.34 | .45 | .50 | .50 | .45 | 47.99 | 43.32 | 36.65 | 42.12 | .01 |
| 3.64 | .27 | .28 | .28 | .26 | 49.69 | 43.88 | 46.05 | 42.77 | .00 |

TABLE 2.—Continued.

(b) Visco Jet 43 070 Lohm

| Pressure drop across visco jet, psia | Flow rate, lbm/hr | | | | Visco jet inlet | | Visco jet outlet | | Quality |
|--------------------------------------|-------------------|--------------|-----------------------|----------------------------|-----------------|-----------------|------------------|-----------------|---------|
| | Measured | Lee equation | Modified Lee equation | 0.9x modified Lee equation | Pressure, psia | Temperature, °R | Pressure, psia | Temperature, °R | |
| 34.08 | 0.28 | 0.35 | 0.30 | 0.27 | 37.09 | 41.22 | 3.00 | 31.16 | 0.15 |
| 21.29 | .25 | .28 | .26 | .24 | 40.95 | 42.11 | 19.65 | 39.61 | .05 |
| 3.43 | .11 | .11 | .11 | .10 | 39.14 | 37.35 | 35.71 | 43.32 | .00 |
| 2.71 | .09 | .10 | .10 | .09 | 38.16 | 42.25 | 35.45 | 43.50 | .00 |
| 37.56 | .30 | .37 | .32 | .28 | 40.60 | 41.08 | 3.04 | 31.15 | .15 |
| 41.29 | .29 | .38 | .32 | .29 | 44.32 | 43.01 | 3.03 | 31.09 | .18 |
| 13.59 | .19 | .22 | .21 | .19 | 47.07 | 44.10 | 33.48 | 42.87 | .03 |
| 53.18 | .36 | .45 | .40 | .36 | 56.48 | 37.44 | 3.30 | 31.60 | .10 |
| 38.64 | .31 | .38 | .38 | .35 | 57.11 | 37.13 | 18.47 | 36.70 | .00 |
| 17.36 | .21 | .26 | .26 | .23 | 57.16 | 37.37 | 39.80 | 36.90 | .00 |
| 4.99 | .12 | .14 | .14 | .12 | 57.13 | 37.84 | 52.14 | 46.13 | .00 |
| 17.73 | .23 | .25 | .25 | .22 | 57.18 | 44.13 | 39.45 | 44.20 | .01 |
| 4.07 | .12 | .12 | .12 | .11 | 56.70 | 43.71 | 52.64 | 46.20 | .00 |
| 36.10 | .31 | .36 | .33 | .29 | 56.59 | 44.12 | 20.50 | 39.93 | .08 |
| 53.32 | .32 | .43 | .35 | .31 | 56.51 | 44.57 | 3.19 | 31.32 | .20 |
| 44.28 | .29 | .39 | .32 | .29 | 47.33 | 44.10 | 3.05 | 31.18 | .19 |
| 25.28 | .26 | .30 | .28 | .25 | 44.87 | 43.45 | 19.59 | 39.64 | .08 |
| 32.98 | .31 | .36 | .32 | .29 | 36.15 | 36.43 | 3.17 | 31.33 | .09 |
| 31.59 | .27 | .34 | .30 | .27 | 34.71 | 39.97 | 3.12 | 31.23 | .13 |

(c) Visco Jet 86 960 Lohm

| | | | | | | | | | |
|-------|------|------|------|------|---------|---------|-------|---------|------|
| 51.58 | 0.18 | 0.22 | 0.20 | 0.18 | 54.38 | 37.40 | 2.80 | 31.04 | 0.11 |
| 30.53 | .11 | .17 | .17 | .15 | 54.54 | 37.21 | 24.02 | 41.11 | .00 |
| 12.95 | .08 | .11 | .11 | .10 | 54.55 | 37.64 | 41.59 | 44.59 | .00 |
| 5.42 | .06 | .07 | .07 | .06 | 54.21 | 38.31 | 48.80 | 45.84 | .00 |
| 3.27 | .05 | .05 | .05 | .05 | 54.05 | 45.16 | 50.78 | 45.90 | .00 |
| 14.09 | .06 | .11 | .10 | .09 | 54.27 | 45.76 | 40.19 | 44.40 | .04 |
| 30.65 | .12 | .16 | .14 | .13 | 54.18 | 45.89 | 23.54 | 40.97 | .10 |
| 50.19 | .18 | .22 | .19 | .18 | 53.04 | 37.00 | 2.85 | 30.81 | .10 |
| 49.18 | .14 | .20 | .16 | .14 | 51.90 | 45.21 | 2.72 | 30.72 | .21 |
| 38.55 | .15 | .19 | .17 | .15 | 41.34 | 36.92 | 2.79 | 30.74 | .10 |
| 39.19 | .14 | .19 | .15 | .14 | 41.91 | 42.41 | 2.72 | 30.71 | .17 |
| 22.61 | .10 | .14 | .13 | .12 | 42.80 | 42.35 | 20.19 | 39.20 | .06 |
| 12.19 | .08 | .10 | .10 | .09 | 42.91 | 43.80 | 30.73 | 41.84 | .04 |
| 33.69 | .14 | .18 | .16 | .15 | 36.39 | 35.67 | 2.70 | 29.68 | .09 |
| 21.97 | .11 | .14 | .14 | .13 | 36.21 | 35.66 | 14.24 | 35.87 | .00 |
| 7.28 | .07 | .08 | .08 | .07 | 34.30 | 35.6935 | 27.02 | 36.46 | .00 |
| 2.66 | .04 | .05 | .05 | .05 | 36.05 | .87 | 33.39 | 38.0241 | .00 |
| 3.33 | .04 | .05 | .05 | .05 | 35.88 | 41.34 | 32.56 | .90 | .00 |
| 6.34 | .06 | .08 | .07 | .07 | 35.97 | 41.73 | 29.63 | 41.24 | .01 |
| 21.72 | .09 | .14 | .13 | .12 | 35.92 | 41.50 | 14.20 | 36.83 | .07 |
| 33.31 | .11 | .17 | .15 | .13 | 35.9242 | 41.13 | 2.61 | 29.61 | .15 |
| 40.15 | .11 | .20 | .18 | .17 | .77 | 33.80 | 2.63 | 29.57 | .07 |
| 40.16 | .09 | .19 | .15 | .14 | 42.72 | 43.07 | 2.57 | 29.51 | .18 |
| 27.92 | .11 | .16 | .14 | .13 | 42.12 | 42.31 | 14.20 | 36.90 | .08 |
| 27.90 | .13 | .16 | .16 | .15 | 42.10 | 34.20 | 14.20 | 36.63 | .00 |
| 12.03 | .09 | .11 | .11 | .10 | 42.13 | 34.44 | 30.10 | 41.39 | .00 |
| 12.07 | .08 | .10 | .10 | .09 | 42.26 | 43.67 | 30.19 | 41.90 | .04 |
| 3.66 | .05 | .06 | .06 | .05 | 42.59 | 43.60 | 38.94 | 43.69 | .01 |
| 2.99 | .05 | .05 | .05 | .05 | 42.05 | 35.50 | 39.06 | 42.81 | .00 |

TABLE 2.—Concluded.

(d) Visco Jet 252 300 Lohm

| Pressure drop across visco jet, psia | Flow rate, lbm/hr | | | | Visco jet inlet | | Visco jet outlet | | Quality |
|--------------------------------------|-------------------|--------------|-----------------------|----------------------------|-----------------|-----------------|------------------|-----------------|---------|
| | Measured | Lee equation | Modified Lee equation | 0.9x modified Lee equation | Pressure, psia | Temperature, °R | Pressure, psia | Temperature, °R | |
| 47.17 | 0.0722 | 0.07 | 0.07 | 0.07 | 49.67 | 35.4 | 2.5 | 29.5 | 0.08 |
| 35.76 | .0647 | .06 | .06 | .06 | 49.96 | 35.2 | 14.2 | 36.9 | 0 |
| 18.77 | .0465 | .05 | .05 | .05 | 50.36 | 35.2 | 31.6 | 42.3 | 0 |
| 8.04 | .0312 | .03 | .03 | .03 | 50.11 | 35.32 | 42.06 | 44.1 | 0 |
| 2.36 | .0186 | .02 | .02 | .02 | 50.23 | 35.59 | 47.86 | 44.74 | 0 |
| 47.80 | .0733 | .07 | .07 | .07 | 50.3 | 35.07 | 2.5 | 29.32 | .08 |
| 48.25 | .0623 | .07 | .06 | .06 | 50.86 | 44.84 | 2.6 | 29.5 | .21 |
| 37.04 | .0530 | .06 | .05 | .05 | 51.22 | 45.33 | 14.19 | 36.9 | .13 |
| 18.12 | .0342 | .04 | .04 | .04 | 51.61 | 45.52 | 33.48 | 42.8 | .05 |
| 10.13 | .0283 | .03 | .03 | .03 | 52.04 | 45.57 | 41.91 | 44.1 | .03 |
| 2.62 | .0152 | .02 | .02 | .02 | 52.32 | 45.72 | 49.7 | 45.1 | .00 |
| 51.10 | .0615 | .08 | .07 | .07 | 53.67 | 37.24 | 2.57 | 29.52 | .10 |

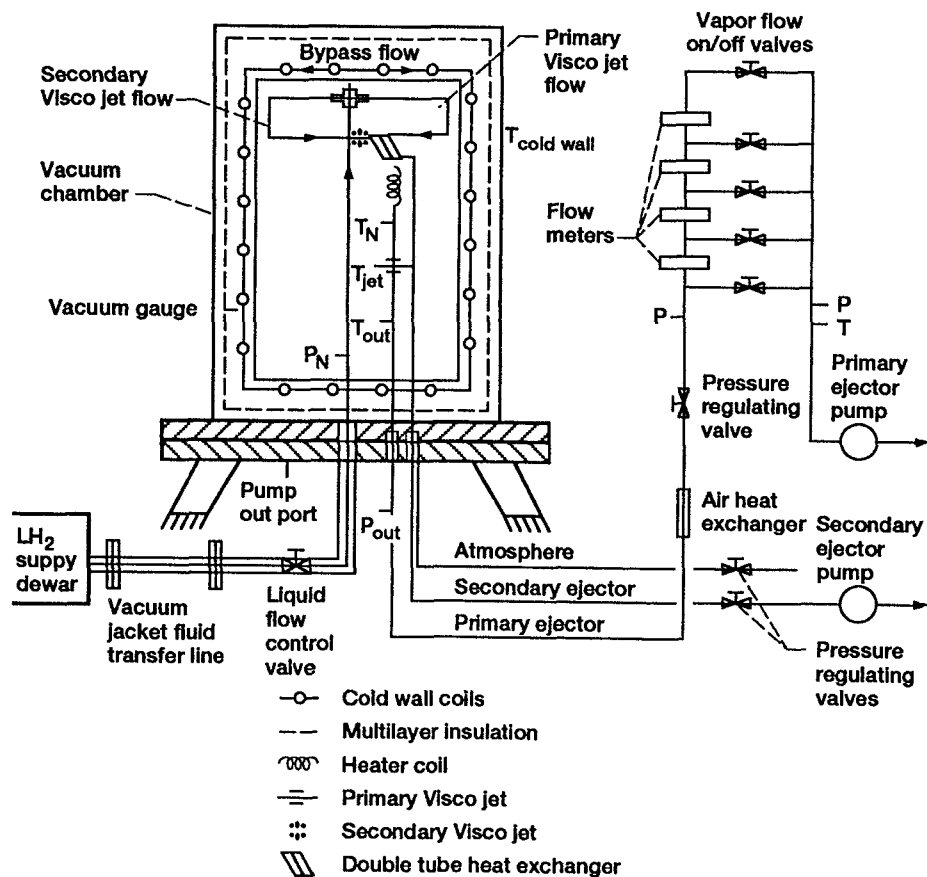


Figure 1.—Joule-Thomson device test rig schematic.

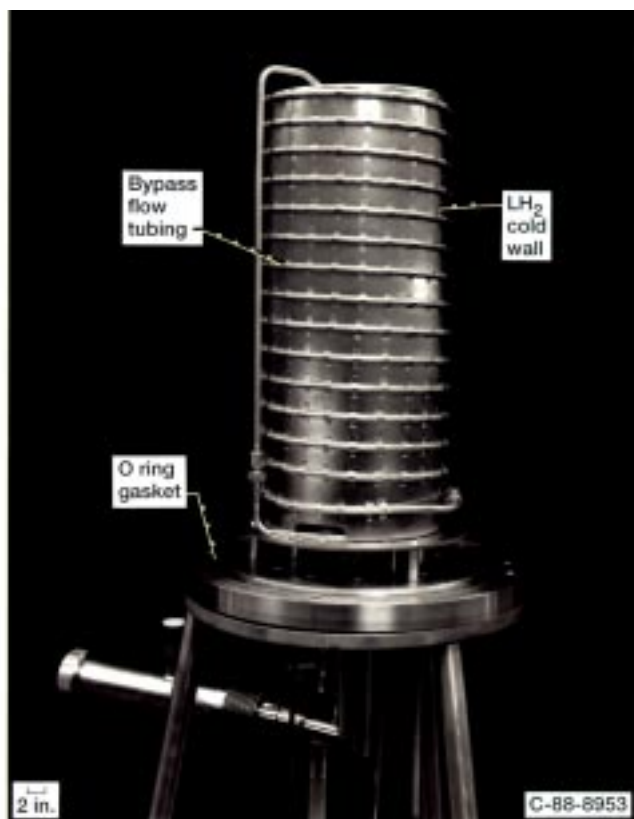


Figure 2.—LH₂ Joule-Thomson device test rig with vacuum chamber removed.

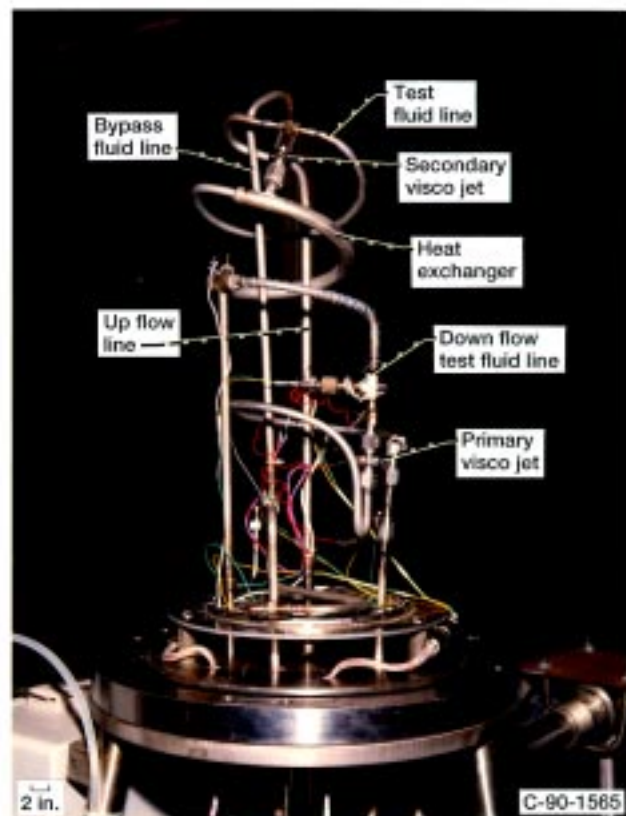


Figure 3.—Flow system with cold wall removed.

An independent Visco "stage" consists of three different patterns which are combined to form a complex fluid passageway

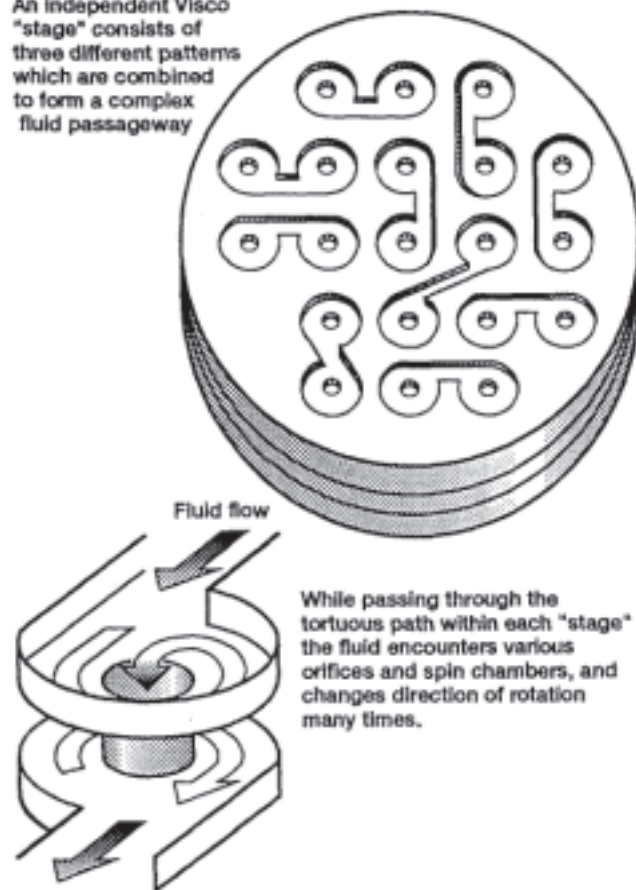


Figure 4.—Visco jet details. (Lee, Technical Hydraulic Handbook, Lee Company, p. 96.)

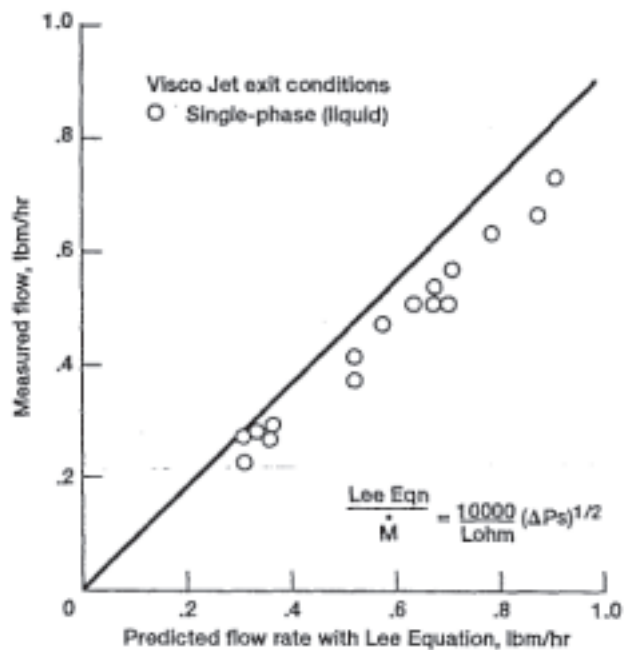


Figure 5.—Measured and predicted values with Lee equation, 17,180 Lohm, LH₂.

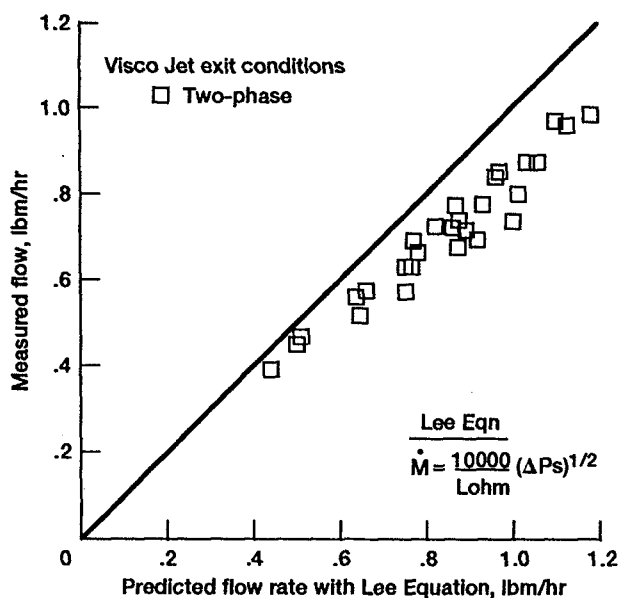


Figure 6.—Measured and predicted values with Lee equation, 17,180 Lohm, LH_2 .

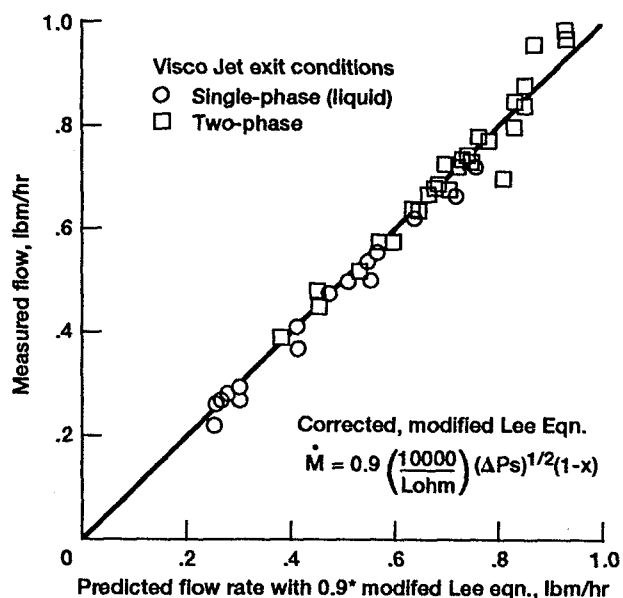


Figure 8.—Measured and predicted values with corrected, modified Lee equation, 17,180 Lohm, LH_2 .

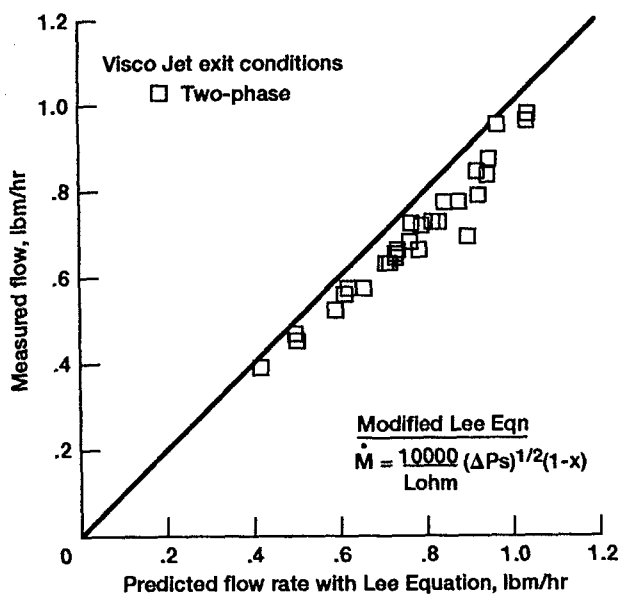


Figure 7.—Measured and predicted values with modified Lee equation, 17,180 Lohm, LH_2 .

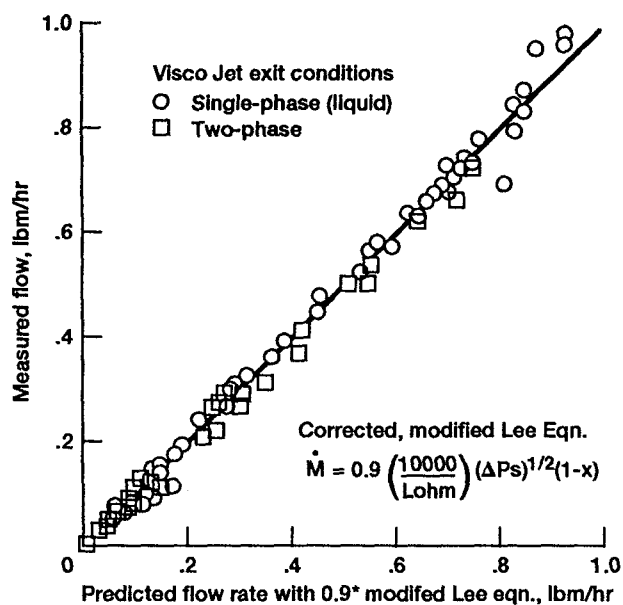


Figure 9.—Measured and predicted values with corrected, modified Lee equation, 17,180, 43,070, 86,960, 252,300 Lohm rating Visco jets - LH_2 .

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| 13. ABSTRACT (Maximum 200 words) Liquid hydrogen mass flow rate, pressure drop, and temperature drop data were obtained for a number of multiple orifice Joule-Thomson devices known as Visco Jets. The present investigation continues a study to develop an equation for predicting two phase flow of cryogenics through these devices. Liquid nitrogen flow data, single (liquid) and two phase, and a data correlating equation that predicted it, was developed and presented in an earlier report. The correlation was a modified version of a flow prediction equation from the Visco Jet manufacturer. Current effort extends this equation by testing it with liquid hydrogen. The test apparatus design allowed isenthalpic expansion of the cryogen through the Visco Jets. The data covered a range of inlet and outlet operating conditions. The inlet pressure and temperature range was 27 to 65 psi and 34 to 46 R, respectively. The outlet pressure and temperature range was 2.5 to 60 psi and 26 to 46 R, respectively. The mass flow rate data range—single phase or two phase—was 0.015 to 0.98 lbm/hr. The manufacturer's equation was found to overpredict the single phase hydrogen data by 10 percent and the two phase data by as much as 27 percent. Two modifications to the equation resulted in a data correlation that predicts both the single and two phase flow across the Visco Jets. The first modification was of a theoretical nature, and the second strictly empirical. The former reduced the spread in the two phase data. It was a multiplication factor of 1-X applied to the manufacturer's equation. The parameter X is the flow quality downstream of the Visco Jet based on isenthalpic expansion across the device. The latter modification was a 10 percent correction term that correlated 90 percent of the single and two phase data to within a ± 10 percent scatter band. | | | | |
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